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Citation for published version:
Siegert, MJ, Hindmarsh, R, Corr, H, Smith, A, Woodward, J, King, EC, Payne, AJ & Joughin, I 2004, 'Subglacial Lake Ellsworth: A candidate for in situ exploration in West Antarctica' Geophysical Research Letters, vol 31, no. 23, L23403, pp. 1-4., 10.1029/2004GL021477

Digital Object Identifier (DOI):
10.1029/2004GL021477

Document Version:
Publisher final version (usually the publisher pdf)

Published In:
Geophysical Research Letters

Subglacial Lake Ellsworth: A candidate for *in situ* exploration in West Antarctica

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Received 13 September 2004; revised 23 October 2004; accepted 10 November 2004; published 14 December 2004.

[1] Radio-echo sounding reveals a 10 km-long lake beneath ~3.4 km of ice near the Ellsworth Mountains in West Antarctica, 20 km from the ice divide. Subglacial Lake Ellsworth is located within a distinct topographic hollow, which is ~1.5 km deeper than the surrounding bed. Judging by bed slopes flanking the lake, the water depth is at least 10s of metres. Calculations of basal temperature reveal the ice base to be warm both now and during full glacial periods. As the environments of subglacial lakes are broadly similar, life may be expected in Lake Ellsworth as in any other. Given this, its physical characteristics, and the fact that the West Antarctic Ice Sheet has been accessed on several occasions, Lake Ellsworth is an excellent candidate for *in situ* examination. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 6207 Planetology: Solar System Objects: Comparative planetology; 9310 Information Related to Geographic Region: Antarctica; 9604 Information Related to Geologic Time: Cenozoic. **Citation:** Siegert, M. J., R. Hindmarsh, H. Corr, A. Smith, J. Woodward, E. C. King, A. J. Payne, and I. Joughin (2004), Subglacial Lake Ellsworth: A candidate for *in situ* exploration in West Antarctica, *Geophys. Res. Lett.*, *31*, L23403, doi:10.1029/2004GL021477.

1. Introduction

[2] It is now an established hypothesis that Antarctic subglacial lakes house unique forms of life [*Priscu et al.*, 1999] and hold detailed sedimentary records of past climate change [*Siegert*, 2000]. Testing this hypothesis requires *in situ* examination. The direct measurement of subglacial lakes has been debated ever since the largest and best-known lake, named Subglacial Lake Vostok, was identified as having a deep water-column [*Kapitsa et al.*, 1996]. Much attention has been placed on Lake Vostok as a lake in which exploration should take place. This is, in part, because we know more about this lake than any other subglacial lake. For example, it is the only lake examined in detail by airborne geophysical techniques [*Studinger et al.*, 2003]; it is the only lake that has been sampled indirectly (by the refrozen lake water at the base of the Vostok ice core [*Jouzel et al.*, 1999]); and it is the only lake in which water circulation has been modeled [e.g., *Wüest and Carmack*, 2000; *Mayer et al.*, 2003]. In fact, our knowledge of subglacial lakes in general has come about from work on Lake Vostok [e.g., *Siegert et al.*, 2001].

[3] Unfortunately, because Lake Vostok is so large (over 14,000 km^2 by area), it would take several seasons of dedicated fieldwork to measure and comprehend its two cavities [*Studinger et al.*, 2004] in a detailed manner. For this reason, and because of environmental and logistical concerns, the Subglacial Antarctic Lake Exploration group of specialists, set up by the Scientific Committee on Antarctic Research to consider and recommend mechanisms for the international coordination of a subglacial lake exploration programme, state that exploration of smaller lakes is a "prudent way forward" [*Priscu et al.*, 2003].

[4] Since the original inventory of subglacial lakes [*Siegert et al.*, 1996], over sixty news lakes have been discovered. The current total stands at over one hundred and forty. However, no single lake has yet been proposed as a candidate for first *in situ* investigation. In this paper, we present information on a 10-km long subglacial lake near the Ellsworth Mountains in West Antarctica (named Subglacial Lake Ellsworth), and discuss why this lake is the prime candidate for future exploratory subglacial lakes research.

2. Radio-Echo Sounding Data

[5] Direct knowledge of Lake Ellsworth is restricted to one airborne radio-echo sounding (RES) line, acquired in 1977–78 (Figure 1). Subglacial lakes can be identified on RES records by the presence of the following characteristics [*Oswald and Robin*, 1973; *Siegert et al.*, 1996]: (i) strong reflections from the ice-sheet base, which appear bright on film records and are typically 10–20 dB stronger than adjacent ice-bedrock reflections, (ii) echoes of constant strength along the track, indicative of an interface which is very smooth on the scale of the RES wavelength, and (iii) a flat topographic character. These conditions are met between 28 and 38 km (at ~79°S, 90°W) (Figure 2a). Although the smooth, specula-type reflector is difficult to appreciate in Figure 2a (as these data were 'depth differentiated' on site in an *ad hoc* manner to 'brighten' the lower part of the image), it is illustrated well in a magnified 4 km long RES section (which is non-differentiated) from the centre of the lake (Figures 2b and 2c).

[6] The mean gradient of the lake surface reflector is 0.02 (about −11 times the ice surface slope), which is expected provided the lake is in hydrostatic equilibrium with the overriding ice. The gradient of the bed surrounding Lake Ellsworth is at least twice as great as the lake, which

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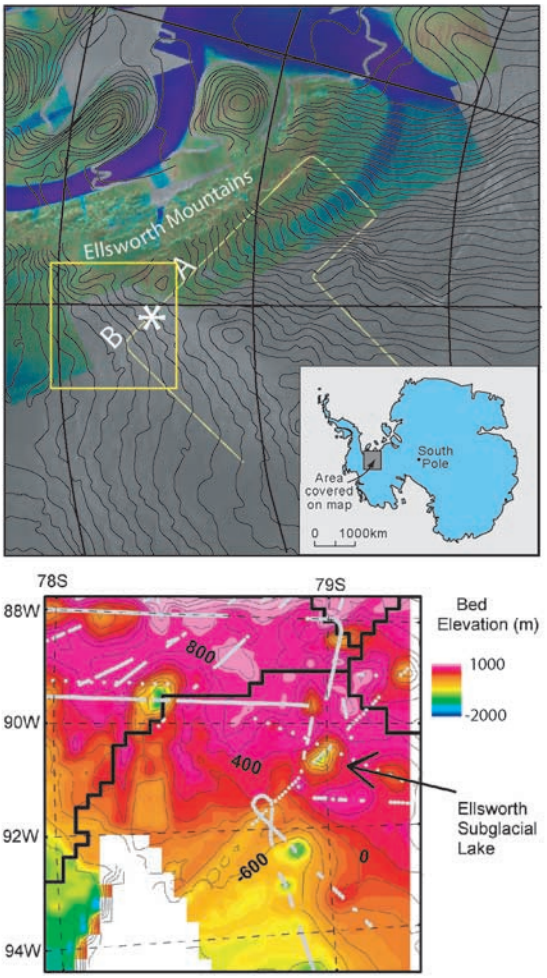

Figure 1. (top) The location of Lake Ellsworth (shown as an asterisk). The position of the RES flightline (yellow line) is shown superimposed against an InSAR surface ice velocity map of the region (green represents lower velocities, purple corresponds to higher velocities, e.g., Rutford Ice Stream to the north of the Ellsworth Mountains). The position of transect AB (Figure 2) is noted. (bottom) Bed elevation surrounding Lake Ellsworth. RES flightline data are shown in grey. Contours are in 200 m intervals.

implies that the depth of the lake could be of the order of 100s of metres. The surface gradient of the lake is important as, like Lake Vostok, it may cause differential rates of melting/freezing across the lake [*Studinger et al.*, 2004], which in turn excite circulation of water within the lake [*Siegert et al.*, 2001]. Lake Ellsworth is located about 20 km from the ice divide and so ice velocity in the horizontal direction over the lake is expected to be no greater than a few metres per year. The bed surrounding the subglacial lake reveals that it occupies a distinct subglacial depression across the foothills of the Ellsworth Mountains (Figure 2b).

[7] The slope of the ice base across Lake Ellsworth is not entirely constant; being concave over the lake's upstream side and convex across its downstream side. In other words, the ice sheet 'sags' as it flows onto the lake, and buckles against the side wall as it re-grounds (Figure 2d). The same features have been identified over Lake Vostok (Figure 2e) and are an expected characteristic of a deep-water subglacial lake. In the cases of both lakes, the strength of the reflections from the ice-water interface varies near the shores, as a consequence of the reflector's shape (Figures 2d and 2e).

3. Basal Thermal Conditions

[8] Numerical ice flow modeling and thermodynamic evaluations of the ice sheet allow us to be confident that the subglacial environment above Lake Ellsworth is warm, and that basal melting should be expected at a significant level both now and in the past.

3.1. Thermodynamic Calculations

[9] Using a 1-D thermodynamic equation (after *Robin* [1955], as applied to subglacial lakes by *Siegert and*

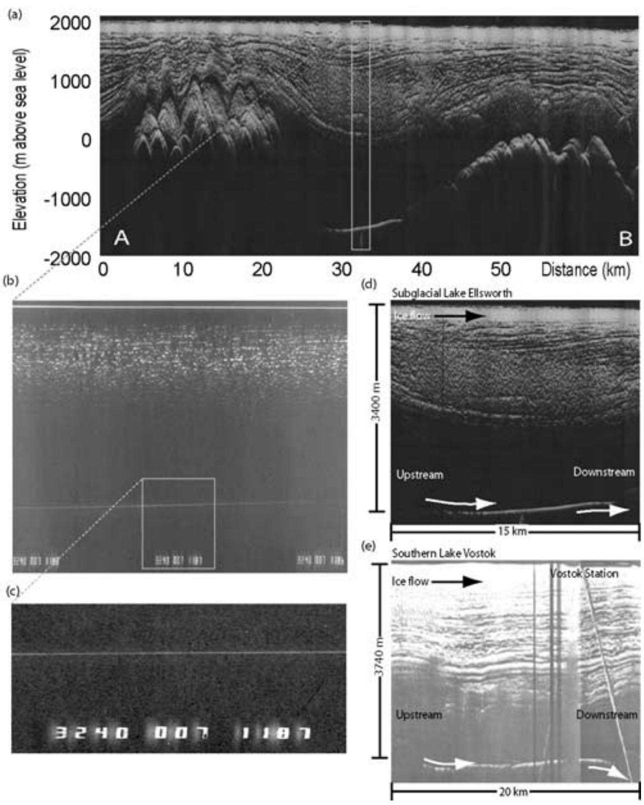

Figure 2. RES data from Lake Ellsworth. (a) Raw RES transect AB (Figure 1). The subglacial lake is located between 28 and 38 km. These RES data were acquired using a depth-differentiated system, in which the signal was amplified in proportion to two-way travel time. Note that, despite this amplification, the basal signal is weak either side of the subglacial lake. (b) Magnified section of RES data over the central region of Lake Ellsworth (located by the box in Figure 2a). These data are in non-differentiated form. (c) Further magnification of RES data shown in Figure 2b, which demonstrates the specula, flat and smooth nature of the reflector, and its steady along-track strength. The slopes of the ice-water interfaces over the upstream and downstream sides of (d) the Ellsworth subglacial lake, (e) the southern end of Lake Vostok (Vostok Station is denoted by the surface parabola). Figure 2e is adapted from *Siegert and Ridley* [1998].

Dowdeswell [1996]), the geothermal heat required for the ice base to melt over the subglacial lake, beneath 3.5 km of ice (i.e., −3°C) assuming a mean annual surface temperature of −30°C and ice accumulation of 17 cm yr^{-1} [*Giovinetto and Bentley*, 1985], is 52 mW m^{-2}. At the last glacial maximum, according to the numerical model of *Huybrechts* [2002], ice thickness over Lake Ellsworth was 250 m greater than at present, air temperatures were ∼8°C cooler and accumulation rates were about 50% of modern values. In this case, the required basal heat flux is only 47 mW m^{-2}. The basal heat flux calculated in West Antarctica from temperature gradients in boreholes is around 70 mW m^{-2} [e.g., *Hulbe and MacAyeal*, 1999]. Hence, basal heating at the level expected is sufficient for the subglacial lake to exist during both the present interglacial and the LGM.

3.2. Ice Flow Modeling

[10] The RES transect is positioned approximately orthogonal to surface contours (Figure 1) and so can be thought of as being roughly parallel to the flow of ice. Because of this, a two-dimensional numerical ice flow model can be employed (as detailed briefly below and by *Siegert et al.* [2003]), using the topographic, englacial and surface elevation boundary conditions detailed in Figures 1 and 2, to quantify the rates of subglacial melting over the lake.

[11] The model is specifically targeted at using the internal layer architecture to invert for basal melting. The appropriate basal boundary condition is one of zero basal shear stress over the subglacial lake. This means that, as in an ice shelf, the vertical velocity must vary linearly with depth, which allows us, by ensuring that the model predictions of isochron (internal layer) distribution match observations, to invert for the basal melt. This can then be used to infer the heat flux from the lake, which can either be due to geothermal heating or, more likely, some combination of this and heating anomalies due to water circulation and subglacial melting/freezing. We are not required to estimate stress gradients as we know the basal tangential stress (zero) and can, therefore, automatically correct for the effect of longitudinal stresses.

[12] Particle flow paths can be determined by matching predicted isochronous surfaces (which are related to the particle tracks) to internal RES layers (Figure 2) (as in work by *Siegert et al.* [2003]) through adjustments to the surface ice accumulation and basal melting/freezing.

[13] Assuming the ice sheet to be in steady state, model results reveal two features concerning surface and basal mass balance over Lake Ellsworth (Figure 3). First, as ice flows over the lake basal melting is expected at a rate comparable to the surface accumulation rate (which near the ice divide is ∼17 cm yr^{-1}). While this melt rate is significantly greater than calculated for Lake Vostok, it is comparable to the situation in Lake Vostok in terms of its value as a proportion of the surface accumulation rate. As melting is the driving force behind water circulation [*Mayer et al.*, 2003], the enhanced rates of melting predicted by the model may lead to circulation in Lake Ellsworth being stronger than Lake Vostok (and many other subglacial lakes). Upstream of Lake Ellsworth a small region of basal accretion is modeled at a rate of 20 cm yr^{-1}. It is not yet known whether this freezing rate is real, or whether three-dimensional flow of ice (not accounted for in the model) complicates ice flow upstream of the lake and influences the internal layer structures above. Second, ice surface accumulation above the lake region is calculated to be noticeably greater (by ∼40%) than on either side of the lake. Clearly, to model the observed internal architecture over Lake Ellsworth, significant adjustments to the rates of surface and subglacial mass balances are required.

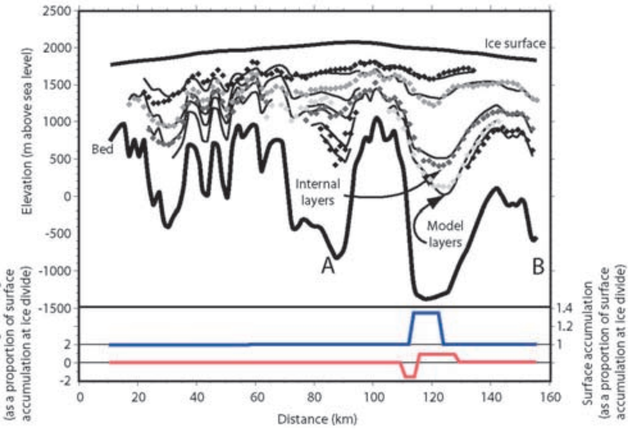

Figure 3. Numerical modeling of ice flow and mass balance along AB (located in Figure 1). The upper panel shows model results, where internal layers (thin lines) are superimposed over real positions of internal layers (dots) (Figure 2). Lower panel shows the relative proportions of surface accumulation (blue line) and basal melting/freezing (red line) required to achieve the internal layer distribution shown in the upper panel.

4. Advantages of Lake Ellsworth for Exploratory Research

[14] The following nine points collectively demonstrate why Lake Ellsworth is a prime candidate for future *in situ* investigation.

[15] First, the base of the East Antarctic Ice Sheet has never been reached by drilling, and this makes the planning of East Antarctic lake exploration particularly difficult in terms of environmental protection. However, there have been numerous occasions when the base of the West Antarctic Ice Sheet has been reached, sampled and measured [e.g., *Gow et al.*, 1968]. In particular, ice-water contacts within West Antarctica have been analysed by *in situ* studies several times [*Kamb*, 2001]. Hence, although the environmental issues relating to the exploration of Lake Ellsworth are important, they may not be as difficult to overcome as the issues connected with East Antarctic subglacial lake exploration.

[16] Second, as Lake Ellsworth is located close to the ice divide, drilling from the ice surface into the lake will not be complicated by ice flow.

[17] Third, Lake Ellsworth can be characterised meaningfully in a single field season using seismic surveying and RES as, unlike Lake Vostok for example, it is relatively small (i.e., ∼10 km in length).

[18] Fourth, the lake is accessible through both British and US Antarctic logistic operations (in addition to several other nations).

[19] Fifth, the sediments across the floor of Lake Ellsworth may contain a record of the West Antarctic Ice Sheet history.

[20] Sixth, the geological setting of the lake may be better understood than any other Antarctic subglacial lake, as there is substantial outcrop of rock in the nearby Ellsworth Mountains to get a good appreciation of the local geology.

[21] Seventh, Lake Ellsworth may be representative of other subglacial lake environments. The lake will have pressure and temperature conditions similar to all subglacial lakes, and dissolved gas and clathrates may be present in the water at levels similar to that calculated for Lake Vostok [*McKay et al.*, 2003]. Assuming the lake surface area to be 100 km^2, a water depth of 500 m and a mean melt rate of 10 cm yr^{-1}, the turn-over time of the lake (assuming 100% of the water mixes) will be 5000 years. Thus, if the lake is 150,000 years old, the water may have been replaced 30 times; which is the number *McKay et al.* [2003] use to infer 2.5 litres (gas) per kg of water (and the onset of clathrate formation).

[22] Eighth, the ice-sheet surface elevation over Lake Ellsworth is 2000 m above sea level; more than a kilometre lower than the ice surface over East Antarctic subglacial lakes. Altitude related problems encountered by scientists at the centre of the East Antarctic Ice Sheet will not, therefore, be as much of an issue during the study of Lake Ellsworth.

[23] Ninth, RES data show Lake Ellsworth to be enclosed topographically (Figure 1b), which suggests that it may have existed as long as thick ice covered the depression in which is resides. This means that the lake is likely to be stable with respect to small changes in the overlying ice sheet (i.e., it will not outburst as may happen in lakes that are located in relatively subdued topography [*Dowdeswell and Siegert*, 2002]). It is unlikely that the lake is connected to other lakes, as may be the case at Dome C in East Antarctica, although more RES data are required to be fully confident of the lake's hydrologic isolation.

[24] **Acknowledgments.** MJS acknowledges funding by UK NERC grants NER/A/S/2000/01144 and NER/A/S/2001/01011, and a Philip Leverhulme Prize awarded by the Leverhulme Trust. AJP acknowledge funding from the NERC Centre for Polar Observation and Modelling (CPOM). IJ performed his contribution to this work at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. We thank Chris McKay and an anonymous referee for helpful and constructive reviews.

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